

EFFECTIVENESS OF CONDITION BASED
MAINTENANCE IN ARMY AVIATION

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General Studies

by

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Technology has significantly enhanced our ability to detect and monitor the health and condition of critical components in Army aviation. By combining these technological advances with the existing systems for vibration analysis, we have developed a maintenance management program based on the health condition of the components rather than time-driven inspections and replacements. One vibration analysis program, the Health Usage and Management System (HUMS), developed for the UH-60 Blackhawk, was examined in this study. The purpose of this thesis is to determine whether Condition Based Maintenance (CBM) provides a distinct advantage over phase or time-driven inspections and component replacement in Army Aviation. To answer this question we have identified a series of metrics to assess the efficiency and usefulness of CBM. During the analysis portion of this study we examined two assault helicopter battalions, one HUMS-equipped and one without, and applied these metrics. This study determined that HUMS does provide an advantage in flight hours completed and operational readiness rates, coupled with a marginal decrease in hours of non-mission capable for maintenance reported. While this thesis also found an increase in efficiency in dollars spent per operational flight hour, the data set was too small to draw major conclusions. Recommendations for further study include incorporating this new system into failure mode identification and improved maintenance procedures.

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ACRONYMS

AOAP	Army Oil Analysis Program
CAB	Combat Aviation Brigade
CBM	Condition Based Maintenance
DA	Department of the Army
DoD	U.S. Department of Defense
DSC	Digital Source Collector
FH	Flight hours
FM	Field Manual
FMC	Fully Mission Capable
IPS	Inches Per Second (measure of displacement)
MMH	Maintenance Man Hours
MOC	Maintenance Operational Check
MTF	Maintenance Test Flight
NMC	Non-Mission Capable
NMCM	Non-Mission Capable Maintenance
NMCS	Non-Mission Capable Supply
OEF	Operating Enduring Freedom
OIF	Operation Iraqi Freedom
OR	Operational Readiness
PAM	Pamphlet
PMC	Partially Mission Capable
PMCS	Preventative Maintenance Checks and Services
RPM	Revolutions Per Minute

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CHAPTER 1

INTRODUCTION

In the Army, we strive to establish high standards of performance and readiness in both our personnel and equipment. Whether it is a weapon system or a vehicle, soldiers perform maintenance on their equipment to ensure that it is ready to operate when the time comes to execute the mission. In recent years, the Army has tested an implemented new aircraft systems that monitor vibrations throughout the airframe in order to predict the impending failure of components and provide maintainers with an overall health assessment of the airframe. The overall program is known as Condition Based Maintenance (CBM). This thesis aims to evaluate the effectiveness of CBM over periodic or phase maintenance inspections in Army Aviation.

In the early years, maintenance was only performed when something broke or could not function to accomplish the task. This process of addressing equipment failures after the occurrence is called *corrective maintenance* and still exists today in all Army units. But breakdowns and their subsequent impact on future equipment availability (operational readiness) called for a new method or approach to dealing with equipment and vehicle maintenance.

A more proactive form of maintenance was later developed, focusing in on critical components and common points of failure. Known as *preventative maintenance*, soldiers conduct routine inspections and services, where the equipment or vehicle is checked to find faults and prevent breakdowns from occurring. Preflight and periodic inspections are just a couple of variations of this system that have been adopted in Army Aviation to ensure the safety of the crew and airworthiness of the aircraft.

Phase Maintenance Inspections are the most common form of preventative (and corrective) maintenance used in Army Aviation today. Each periodic or phase inspection (commonly referred to as a “phase”), occurs at a set interval based on the number of flight hours completed on a given airframe. During the phase, all major components (powerplant, drivetrain, avionics, etc.) as well as major structural members are inspected and replaced based on certain parameters. Most components are damaged due to friction, tension or torque from the constant vibration and physical stresses imposed on the helicopter during flight.

Nearly all components are replaced when they are found to show signs of wear, fatigue, or cracks indicating impending failure of the component. These are usually detected by maintenance personnel during scheduled inspections or found when the helicopter does not perform correctly. Other components are replaced based on a manufacturer’s predicted failure time, or Time Between Overhaul (TBO). These components are normally high-wear items like ball bearings or high speed shafts which move or rotate at speeds greater than 20,900 revolutions per minute¹. But there are two major inefficiencies that arise with the use of this system.

The first is that the TBOs are merely projected failure rates established by the component manufacturer, not the actual failure point of the component. Instead they are based upon a safety factor of 3². This means that if the bearings in an oil cooler assembly reached material failure (on average) at 750 hours of flight operation, the replacement time on the component would be set at 250 hours. This allows a margin of safety between item replacement and component failure. Unfortunately, it also reduces the

item's lifetime use significantly and increases the amount of funds spent on purchasing and stocking replacement components based on a shortened item lifespan.

The second inefficiency centers around the maintenance actions and their adverse effects on mission readiness. If an aircraft reaches its 250 hour inspection point, it is pulled off the flight line, cowlings and panels removed, and sometimes the component itself is removed from the airframe to complete the procedure, creating a high demand on maintenance personnel and artificially inflating the number of man-hours expended. The time it takes to remove, inspect, order a replacement, and install the new part negatively impact the operational readiness (OR) of the aircraft and its ability to conduct future missions. In addition, once the component replacement is complete, a maintenance operational check (MOC) and possibly a maintenance test flight (MTF) may be required before the aircraft is deemed airworthy and released back to the flight company for missions. All of this time expended and costs incurred begs the question: Is there a better way to predict component failure?

New technologies expand our ability to detect flaws and impending failures in components, and provide us with new possibilities in performing maintenance. Within the last twenty years, the aviation industry has quickly moved ahead with applying these new technologies to maintenance programs. Aviation maintainers started utilizing magnetic flux, ultrasound, and other non-destructive inspection (NDI) techniques to detect cracks in critical components. But these technologies still require technicians to remove cowlings, other items and hardware, and sometimes the component itself, in order to inspect it. In addition to the time it takes to inspect the component, the removal of certain components (especially those directly tied to control surfaces), requires certain

maintenance operational checks (MOCs) and sometimes a maintenance test flight (MTF) to ensure the aircraft is airworthy. While the technology enables us to detect flaws in the item it does not predict the failure of the component.

These new ideas have led Army aviation maintenance managers back to rethinking the older approaches to replacing components blindly based on their time of use. Instead the aim is to find ways to measure the wear and tear on each item individually, replacing it only when it is approaching failure. This new approach, of maintenance based on the condition of the component rather than a phased replacement of the item, has become known as Condition Based Maintenance (CBM).

CBM is a program that monitors the health and usage of the component in order to predict its failure and extend operational usage of the item as well as track the overall condition of the airframe. An example should suffice to explain what is meant by the health and usage of the item. Two identical cars are driven over a 5 year span of time. One car is kept in a garage and driven an hour a day on the highway to and from work, the other is kept outside and driven for one hour a day in the city with constant stop and go traffic. Would the wear on the engine, drivetrain, and tires be the same with both vehicles even assuming they have driven the same distance and time over the past five years? Most people would agree that there would be substantial differences in vehicle condition based on varied road conditions, temperatures, acceleration/deceleration of the automobile and so on. The health and usage aspect of CBM focuses in on several key indicators to determine and predict the condition of components in order to better assist maintainers with predictability and timeframe for item replacement.

The Goodrich Corporation developed one of the first CBM systems for Army Aviation in 2002. The Integrated Vehicle Health Management System (IVHMS) consists of an array of sensors, remote data concentrator (RDC), cockpit display unit (CDU), Data Storage and Transfer Unit (DTU), a central processing unit all connected with fiber optic cable. Together the IVHMS provides monitoring and diagnostic capabilities for rotor track and balance, engine health monitoring, gearbox and drivetrain health monitoring, and structural usage and fatigue tracking for the lifetime of the component. This system enhances the operational readiness and safety of the airframe through the early identification of damaged or degraded components.

The instrumentation onboard the aircraft collects usage data during aircraft operations. From ground runs, take offs and landings, to hovering flight and all of the various flight regimes, IVHMS is able to monitor, record and calculate the usage and health of individual components on the airframe. This data is later transferred to a ground terminal which stores and monitors all of the aircraft assigned to the unit and can compare changes in indications through trend analysis in order to predict future component failure.

From an aviation maintenance officer's perspective, the IVHMS facilitates the performance of maintenance operation checks (MOCs), maintenance test flights (MTFs), and other diagnostic activities. Vibrations are automatically recorded during normal flight operations, thereby reducing the requirement for the above mentioned MOCs and MTFs. The system analyzes the sample data and provides adjustment recommendations to the maintenance personnel on the ground. In the event of a limitation exceedance, such as a rotor overspeed or over-torque of an engine, IVHMS records the data and

makes it available to maintenance personnel for further troubleshooting following the flight. By reducing or eliminating the need for MOCs and MTFs we cut down the number of needless additional maintenance flight hours and increase component use time on an airframe thereby saving future flight time and dollars spent.

The theory behind CBM is clear: component wear and failure can be accurately predicted through vibration analysis. The IVHMS uses a series of sensors or accelerometers to detect and measure vibrations in the aircraft. The accelerometer measures the vibration frequency and further differentiates between the displacement, velocity and acceleration of the vibration at the point of interest. This allows the IVHMS to analyze and identify possible imbalance in the system.

There are three types of accelerometers used in the Integrated Mechanical Diagnostic (IMD) system: uni-axial (along a single axis), bi-axial (along two separate axes), and tri-axial accelerometers (along three separate axes). Each sensor is placed at a critical location on the airframe in order to monitor a specific component. These accelerometers can detect vibration discrepancies from an imbalance, misalignment, mechanical looseness, gear mesh, rotor systems, mechanical impedance and natural frequency.

Imbalance often occurs with components that rotate at high speeds and requires vibration analysis and tuning to balance a high speed shaft, oil cooler or tail rotor driveshafts. Misalignment is very similar to imbalance and is usually attributed to mechanical flaws or faulty maintenance. Mechanical looseness displays itself with a large number of harmonics in the vibration spectrum and often precedes the failure of a component. A good example of this is present with the main rotor damper bearings. This

assembly serves as a hydraulically assisted damper for main rotor blade lead and lag, but often begin to exhibit signs of mechanical looseness due to a loss of hydraulic fluid due to a differential in temperature or bearing wear. Gear mesh occurs when the frequency is equal to the number of teeth in the gear times the rotational speed (RPM) of the gear. This is usually detected during initial transmission break in or during transmission breakdown/failure. Rotor system is very similar to the characteristic of an imbalance but deals with vibrations that occur once per revolution of the blade passing frequency (number of blades times RPM). Primary maintenance tasks involving rotor system smoothing include track and balance main and tail rotor systems. Mechanical impedance is a frequency created through force friction in the system, usually illustrating a failed bearing in the system. And finally *natural frequency*, is the frequency an object will vibrate after the excitation is removed. This is used as a baseline frequency to measure and compare changes in the system.

Goodrich's Health Usage and Management System (HUMS) program integrates this technology in order to detect, measure and track the health of airframe subcomponents. Further investigation shows that it is absolutely necessary to explore the thresholds of each component. At what frequency range will the oil cooler bearing signal impending failure? What is the maximum frequency we can safely operate this component before it must be replaced? While this threshold analysis is not a focus area for this thesis, it represents the scientific bedrock upon which CBM can accurately predict component wear and failure. Westar Aerospace and Defense Group has been granted the data collection contract for CBM. In the future they will be able to take vibration data from across Army Aviation and provide units with safe operating

thresholds for these components as well as standardization of vibration data across all airframes in the Army inventory. Once these thresholds are established, the Army will no longer need to rely on the published TBOs but rather the health of the individual component to determine replacement time. Further, with new technologies we should expect the Army to review current maintenance practices for greater efficiencies in the future

In early 2003, Goodrich Corporation was granted a contract to test its HUMS on several aircraft in the 101st Air Assault Division at Fort Campbell, Kentucky. The IMD systems were to be installed and field tested on airframes from 9-101 Aviation. Over a 2 ½ month span, contractors and maintenance personnel performed the ten day HUMS installation on the battalion's 30 UH-60L Blackhawk helicopters. These airframes were selected to participate in the field testing and data collection program while deployed in support of Operation Iraqi Freedom.

Since then more than 300 UH-60 helicopters have been modified and fielded to more than 6 assault battalions Army-wide. The preliminary results boast significant improvements in operational readiness and flight hours, as well as improved efficiency in maintenance man hours and non-mission capable for maintenance time.

Primary Research Question

Does CBM provide a distinct advantage over phase or time driven inspections and component replacement in Army Aviation?

Secondary Research Questions

How do we measure the overall benefits and costs of CBM?

Can CBM data accurately predict impending component failure and how closely does actual component failure come to established TBOs?

Can component failure be predicted with enough time to provide supply request time?

Does CBM reduce maintenance man hour and test flight requirements? By how much?

Does CBM increase operational readiness rates and flight hours? By how much?

Are there cost advantages to using CBM?

Significance of Research

This topic of research represents the apex of where technology and innovation meet implementation in today's aviation maintenance system. In light of the recent economic climate and growing national deficit, and the pressures these factors will exert upon defense budgeting in general, this thesis serves to address whether implementing conditioned based maintenance provides a distinct advantage, both practically and financially, over the current phase maintenance and periodic inspection process. The intent of this study is to establish a set of metrics to evaluate the efficiency of CBM as well as make recommendations for changes to maintenance practices and procedures in the future.

Assumptions

All maintenance personnel are created equal. Experienced maintenance officers conclude that maintenance is part science and art. In this study a major assumption is made that all maintenance test pilots are equal in order to evaluate like units. This assumption is based upon the standardization of all Army aviation maintenance practices and procedures. Despite minor differences in personnel training or experience, task completion and standardization within the unit will ensure quality in maintenance actions.

Units are at the same personnel fill level. There is no way to know whether the units were at equal personnel strength, or to compare an offset in manning for mechanics to avionics technicians or airframe repairers. This study assumes that units are at an equal fill in order to equitably compare like battalions. While actual unit fill levels may vary, HRC mandates a personnel fill of 95 or above across deploying divisions. The 101st would have received a priority for fill in preparation for the OIF III/IV deployment in 2005-2006. This assumption relies on an equity of personnel fill by the Division G1 to subordinate brigades and Brigade S1 to subordinate battalions.

Aircraft age and usage are similar. While aircraft age is sometimes a contributing factor to increased maintenance actions, this study assumes that aircraft are of comparable age in comparable units in order to provide a better comparison of battalion performance. Likewise, aircraft usage may differ from one deployment to another or even from different locations during the same deployment. This study assumes that battalion aircraft will share the same mission requirements and area of responsibility throughout the deployment.

Inflation, especially in connection with the cost of replacement components and parts over the 2005-2006 Operation Iraqi Freedom deployment did not materially affect this study.

Limitations

CBM is still in its infancy. While the number of systems installed on airframes in the Army continues to grow, the amount of data to draw from is limited to the reports recorded within the last five years. Furthermore, to effectively compare units with HUMS to units without, attempted to evaluate them when they were at an equal priority level for maintenance and supply and when they were completely dedicated to performing their assigned mission. In summary, the only way to effectively evaluate these units is during deployment.

Comparing deployed units to non-deployed units would not yield an effective sample group for comparison. Hours flown during combat operations will dwarf the hours flown by those same units in garrison. There are several factors involved here to include aircraft shortages, aircraft reset, and preset/modification to name a few. Army aviation as a whole is short a combat brigade's worth of aircraft due to accidents and aircraft losses³. This causes aviation unit commands to transfer airframes to deploying units upon completion of previous combat deployments. Aircraft reset is a program which overhauls and replaces a long series of components following a unit's deployment to OIF/OEF. Reset will normally span 90 to 120 days per aircraft and significantly reduce the battalion's ability to conduct currency training and progressions, as well as fly operational training for upcoming deployments (MRE/MRX). Pre-deployment modifications or preset, often conducted in conjunction with aircraft reset, further

segregates the airframe from participation in unit training activities. While CBM may provide garrison units with a distinct advantage where repair parts and maintenance personnel are at a premium, evaluating deployed units against garrison units would not yield an equal comparison.

Reporting potential or impending failures is difficult. Engines, gearboxes or aircraft saved are often left unreported, making the true financial savings of CBM difficult to ascertain.

Battalion to battalion comparison. OEF units are now task organizing so the number of UH-60 aircraft in a unit will vary from 30 to as low as 8 between battalion and task force organizations respectively. This study will only look at battalions with equal aircraft in OIF. In order to rectify this issue in other data comparisons, all metrics should be evaluated against the number of aircraft reported.

Research Design

The research design utilized in this study is a qualitative analysis of flight data and overall performance of two units over a five year period. It is the intent of the research to determine whether CBM systems on the UH-60 Blackhawk are effective in reducing maintenance costs and aircraft down time and increasing the flight hour and operational readiness of the unit. Chapter 3 defines and evaluates the metrics to be used to measure the efficiency of the CBM system. Chapter 4 analyzes the data according to the metrics described in the previous chapter against two UH-60 Blackhawk assault battalions (a standard and HUMS-equipped battalion) over a five year span to determine the effectiveness of CBM. Chapter 5 presents the conclusions reached and recommendations developed through this research process.

Chapter Conclusion

Chapter 1 has given a background and setting to the problem, outlined the construct of the thesis, and finally, posed research questions and parameters by which the thesis will be researched, considered, analyzed, and presented. These elements will hopefully contribute to the literature used to determine whether CBM provides a distinct advantage over phase based maintenance. The following chapter details the materials and resources that were utilized to aid in the development of this thesis.

¹Department of the Army, Technical Manual (TM) 1-6625-724-13&P, *Operator's, Aviation Unit, and Intermediate Maintenance Manual Including Repair Parts and Special Tools List for Test Set, Aviation Vibration Analyzer (AVA)* (Washington, DC: Government Printing Office, 1999), 33.

²Chris Smith, AMCOM, CBM Director, Email correspondence with author, 22 September 2008.

³COL (P) Warren Phipps, "Aviation Branch Day Briefing," Presentation to ILE Aviation Students, Command and General Staff College, Fort Leavenworth, Kansas, August 2008.

CHAPTER 2

LITERATURE REVIEW

Research Material Overview

The literature used in the formulation of this thesis varied significantly from technical texts to the collection and tracking of aircraft maintenance and unit operational readiness reports. Information and data collection is limited to the past years due to the infancy of the CBM system. The initial sources dealt with the maintenance actions from an Army Field and Technical manual perspective. From these sources we turned toward periodicals and previous studies conducted on the advantages and disadvantages of conditions based maintenance. Finally, after reviewing the above documents and publications, it was necessary to evaluate the actual raw data to gain an understanding of the overall performance of the HUMS and CBM as a whole. The remainder of this chapter will highlight key points within these sources and evaluate the quality of the information available.

Technical Data Sources

At the beginning of this study, Army Field Manuals, Department of the Army Pamphlets and System Technical Manuals were the first sources examined in order to frame the problem statement and subordinate questions. These sources set the framework for metrics to be discussed in the following chapter, and to evaluate the usefulness of the HUMS in Army Aviation.

The first publication to be referenced in this study is Field Manual 3.04-500, *Army Aviation Maintenance*. This text outlines the basics of aviation maintenance, from the

fundamentals of maintenance and the army maintenance structure to the automation, supply and personnel responsible for keeping the aircraft flying. The primary areas of focus in this field manual are in chapter 6, production control (PC) management and operations, and chapter 7, quality control management and operations. Specifically, chapter 6 details PC duties, responsibilities and reporting which are crucial in understanding where the hard data comes from and the systems and procedures in place for the disposition of the battalion monthly readiness reporting, or 1352 reports. Chapter 7 highlights the procedures for tracking TBOs, NDIs, and AOAP. Other than some background information on the purpose and usefulness of NDI and AOAP for the formulation of chapter 1 of this thesis and an understanding of the tracking of TBO components on the airframe, there was not much helpful information derived from this chapter. Overall, this manual only helps to establish a baseline knowledge and understanding of the aviation maintenance structure and mechanisms in the Army Aviation framework. In addition, it outlines the procedures of battalion maintenance actions on a daily basis.

Army Regulation 700-138, *Army Logistics Readiness and Sustainability*. This manual outlines the monthly reporting procedures and reports for all Army equipment. The primary area of interest is in chapter 3 which outlines the reporting requirements and standards for aviation units on the monthly 1352 report. These reports are submitted by flight battalions or separate aviation units to AMCOM on the 16th of every month. The reporting period spans from the 16th day of the month prior to the 15th day of the current month. The 1352 encompasses the number of aircraft assigned, flight hours completed, operational readiness (OR) or mission capable (MC) hours, partial mission capable

(PMC) hours with breakdowns on supply (PMCS) or maintenance (PMCM), non-mission capable (NMC) hours with breakdowns on supply (NMCS) and maintenance (NMCM), and finally a categorical separation of aircraft downtime into AVUM, AVIM and Depot hours. This regulation outlines aviation maintenance reporting procedures and requirements as well as defines some of the metrics that may be used later to evaluate the effectiveness of CBM.

Department of the Army Pamphlet 738-751, *Functional Users Manual for the Army Maintenance Management System-Aviation (TAMMS-A)*. This publication is an extension of FM 3-04.500, describing in more detail the procedures required for clearing faults, reporting aircraft status, etc. While this text serves no direct use for data collection or further defining metrics, it does bridge the gap in understanding of what is required to bring a down aircraft up to mission capable status for reporting purposes.

The Goodrich Technical Manual, *System User's Manual for Integrated Vehicle Health Management System (IVHMS)*, is the last of the technical publications examined in this thesis. It is key for bridging the gap between the technology and the data and provides detailed information on the theory of vibration analysis, measurement and failure detection. System information describes the purpose of each component and the data collected from each sensor. While this manual was very interesting, it only provided useful information for the formulation of chapter 1.

Periodicals and Previous Studies

Several studies were examined and evaluated while researching this thesis. But aside from all of the research, it is important to understand where the researcher and data came from. Some originate from agencies within Redstone Arsenal in Huntsville,

Alabama and must be scrutinized for their objectivity. Army Aviation and Missile Command (AMCOM) and Aviation Missile Research, Development and Engineering Center (AMRDEC) both support the idea that CBM provides the maintenance commander with a significant advantage but both have vested interest in supporting the CBM program.

The first article is from a January 2006 edition of *Army* magazine, featuring a presentation made by Major General James Pillsbury, former commander, Life-Cycle Management Command, U.S. Army Aviation Command (AMCOM). The article highlights CBM as well as its applications and advantages at the tactical level. Pillsbury mentions the IMD-HUMS equipped battalion in Iraq that will be used to evaluate the effectiveness of CBM in this study and highlights several statistics that support the HUMS system in Aviation. These statistics are used to support several of the metrics discussed in Chapter 3 and 4. The data used in this article seems to be unbiased because it pertains to the decrease in MMHs and extension of TBOs due to the utilization of CBM systems.

Another pertinent CBM study is the “Comparison of HUMS Benefits: Maintenance Test Flight hours”, by Joshua Kennedy, Command Analysis Directorate, G-3, AMCOM. The paper aimed to introduce MTF hours as a measure that supports the CBM goal of decreasing the maintenance burden on soldiers through a reduction in maintenance test flight hours performed. Kennedy conducted an assessment of MTF reductions across the airframes in the Army inventory. The majority of the data collected was on the Apache but there were numerous discrepancies in the logbook data restricting the amount of qualified information that can be used. This study is an initial look to

determine whether MTF hours will be a useful operating metric to evaluate the CBM program. Unfortunately, as Kennedy highlighted in his presentation at the 2009 Condition Based Maintenance Conference, there is not enough accurate Blackhawk data to draw upon to conclude that MTFs are an effective metric at this time. As HUMS installations continue and more data is reported from the field, future analysis will be conducted at AMCOM to determine if CBM has reduced the number of MTF hours on our helicopter fleet.

Another study examined during the research for this thesis was the “Aviation System Assessment Program / Reliability Centered Maintenance Analysis for UH-60 Monitored Components” by Jason Lawler, Reliability Team Leader, Engineering Directorate, U.S. Army Aviation and Missile Research, Development and Engineering Center (AMRDEC). This investigation evaluates several monitored components on the Blackhawk and determines the modes of failure and critical indicators for impending failure. It also monitors TBO tracked components to determine how closely the TBO reflects the actual failure of the item. While not incredibly useful in providing metrics for evaluation of CBM, this study proved useful in contributing information on the failure modes for numerous components, as well as a source of data for answering the subordinate questions relating to CBM and the extension of TBOs in chapter 4. In addition, there were several notes regarding AOAP that will be cited in chapter 5.

Flight Data

While the previously stated sources give us understanding of the CBM system from a design, monitor and implementation standpoint, further investigation is required in order to prove the effectiveness of the HUMS system aside from previous studies and

reports. While there seems to be no shortage of compiled data reflecting the advantages of CBM, there is no specific tie to aviation units included in each study or the reporting period included (or excluded for that matter) making it difficult to identify and evaluate the actual raw data. This information and raw data most likely came from the aviation units in the Army in the form of their monthly readiness reports and from the Operating and Support Management Information System (OSMIS).

AMCOM is the proponent for the technical data collection from all readiness reports in aviation. Every month an aviation battalion submits a status report covering the flight readiness of their assigned fleet from the 16th day of the previous month to the 15th day of the current month. These reports outline the type and number of aircraft assigned, the number of flight hours performed, along with the hourly breakdown of FMC, PMC, PMCS, PMCM, NMC, NMCS, NMCM times accrued throughout the reporting period. These elements are critical for effective and unbiased evaluation of the overall flight performance and maintenance effectiveness of an aviation unit, regardless of whether the unit is in reset or deployed. Moreover, the raw data from these reports will be used to establish and evaluate proper metrics for evaluating the effectiveness of the CBM system in chapter 3 and later in chapter 4 for the data analysis of the selected units.

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4. ORGANIZATION HQ 1ST BN, 1ST AVN REGT, 82ND ABN DIV				5. TELEPHONE (Comm/DSN) DSN 236-2260		6. UNIT IDENTIFICATION CODE WDFJAA				7. (Do not write in this space)			
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MISSION DESIGN SERIES	SERIAL NUMBER	ASSIGNMENT AND FUNCTIONAL CODE	HRS. ON HAND DURING REPORT PERIOD	MISSION CAPABLE			NOT MISSION CAPABLE			HOURS FLOWN DURING MONTH	NUMBER OF LANDINGS / TOUGHDOWN AUTO- ROTATIONS	GAINED OR LOST	
				FMC	PMC	NMCS	DEPOT	AVIM	AVUM				
a	b	c	d	e	PMCM	PMCS	g	h	i	j	k	l	m
AH64A	87-0482	AGA	744	417	C2/11		186	0	0	130	18	13/0	
AH64A	87-0483	AGA	744	187		A2/13	0	0	0	544	10	4/0	
AH64A	87-0484	AGA	744	711		A30/25	0	0	0	8	32	44/0	
UH60L	91-09790	BGC	744	629	D2/4	CS2/4	0	0	40	67	29	52/0	
OH58D	87-00729	AGA	744	133			71	540	0	0	03	14/0	
OH58D	87-00737	AGA											LT
OH58D	89-00086	AGA	744	462			166	0	0	116	37	54/0	GT
11. TYPED OR PRINTED NAME, GRADE, AND POSITION OF AUTHENTICATING OFFICER JOSEPH R. HOWELL, LTC AV COMMANDING										12. SIGNATURE <i>Joseph R. Howell, LTC</i>			

DA FORM 1352, APR 93 EDITION OF 1 OCT 79 IS OBSOLETE USAFPC 11 00

Figure 3-2. Sample of a completed DA Form 1352

Figure 1. Sample of a Completed DA Form 1352

Source: Department of the Army, AR 700-138, *Army Logistics Readiness and Sustainability* (Washington, DC: Government Printing Office, 2004).

The Operating and Support Management Information System (OSMIS) database tracks operating and support information for the major weapon and materiel systems in the Army. This database was heavily used for its cost tracking for class IX repair parts, fuel and other POL expenditures. Like the aforementioned flight data, this information is an unbiased compilation of costs from consumables, to include all fuel, oil, and aviation repair parts, in each aviation unit. These elements will be critical in the following chapter as a metric for evaluation, for analysis in chapter 4, and referenced heavily in chapter 5 for the future application and study.

Chapter Conclusion

The review of the limited resources in this chapter has established both a list of references, and a feedstock of data which serves as the foundation for this thesis. These include technical manuals, historical flight data, and the raw funding data for aviation parts, which provide a link into the metrics used in evaluating the effectiveness of CBM in the following chapter. This next chapter evaluates these metrics to determine the validity of their methodology to analyze the effectiveness of CBM systems in Army Aviation.

CHAPTER 3

METHODOLOGY AND METRICS FOR EVALUATION

Metrics Overview

This chapter examines and evaluates the various metrics or variables used to evaluate conditions based maintenance system. This information from the reports highlighted in the previous chapter, will be evaluated in detail in the subsequent paragraphs. Flight hours (FH), operational readiness (OR) rates, non-mission capable for maintenance (NMCM), aviation maintenance repair parts in dollars, maintenance test flights (MTFs), maintenance man hours (MMHs) and aviation safety (Class A, B, C accidents) will be evaluated to determine their effectiveness in quantifying the usefulness of CBM in maintenance operations.

Metrics Defined

The first metric used in analyzing the effectiveness of CBM is the unit's flight hours (FH). The number of flight hours completed by a battalion during a given reporting period is a direct reflection on the unit's overall performance and efficiency of its maintenance program. While an increase in flight hours can be related to so many other factors to include weather, mission load, and parts and labor availability, just to name a few, it is the general hypothesis that HUMS-equipped units will be able to generate more flight hours due to improved maintenance practices. FH data is taken from the DA Form 1352 reports submitted by each battalion monthly and covers the time from 0001 hours the 16th day of the previous month to 2400 hours the 15th day of the current month (for example 0001 hours 16 January 2009 to 2400 hours 15 February 2009). In

this thesis, flight hours serve as a measure of efficiency within the aviation units analyzed. A unit that is able to complete more flight hours over the same reporting period with an equal number of aircraft must have an advantage in its maintenance program.

It is important to highlight the inverse relationship that exists between maintenance and flight hours. Maintenance officers utilize an aircraft flowchart to plot the number of flight hours remaining on each airframe before it reaches phase (major overhaul inspection). The result is a flow of aircraft from high-time to low-time and is managed so that the unit's mission requirements are met while controlling the number of airframes in phase at any one time. The sum of the amount of flight hours for all of the airframes is referred to as the actual banktime of the unit. This is compared against the optimal bank time, computed by multiplying one half times the number of airframes times the phase interval. While this is useful in managing mission flow of aircraft, it is not an overall indication of the maintenance status of the unit. In the short term, a unit can leverage its bank time, or surge, in order to accomplish an especially demanding mission load. But in the long term, a maintainer understands that a subsequent reduction in missions is then required in order to maintain bank time and avoid multiple aircraft in phase at the same time. This is often referred to as the "rob Peter to pay Paul" effect.

Major limitations to this metric include fluctuations between deployment and garrison flying, reset and the unit deployment cycle effects on a unit at homestation, and changes in aircraft numbers. As mentioned previously, a battalion's monthly flight hours can vary as much as 300 hours a month in garrison to 2,300 hours a month on deployment.¹ This is merely a reflection upon the unit being the priority and fully

resourced to complete its assigned mission. As for flight hours at homestation, aviation units often struggle to manage a myriad of tasks while attempting to prepare for the next deployment. During redeployment units often transfer six or more helicopters to units actively deploying in order to make up the shortage of aircraft in the Army inventory.² At homestation, units must undergo aircraft reset which normally takes 90 to 120 days, followed by aircraft modifications for the upcoming deployment. And with all of these tasks, battalion personnel turnover and ramp-up to support mission readiness exercises (MREs) further stretches the unit's capabilities to fly missions and maintain aircrew proficiency. The final concern with the flight hours metric is the change in aircraft numbers. This could be due to a combat loss during a deployment or due to task force configuration, as in Afghanistan. Aviation brigades are now split into task organizations to cover specific regions, each requiring attack, recon, lift and assault assets. The end result is a task force of mixed airframes to perform the multi-faceted mission at hand. These reasons make it difficult to compare battalions' flight hours unless they in a deployed status and with an equal number of airframes.

The next metric used in this thesis is a unit's Operational Readiness (OR) rate. To fully understand operational readiness one must break it down into its basic reportable components: Fully Mission Capable (FMC) and Partially Mission Capable (PMC). FMC is based on the number of hours of reporting time in a monthly reporting period in which an aircraft is available for all operational missions. An aircraft is considered PMC when it can perform some but not all of its missions at an acceptable level of safety. PMC time terminates when the required maintenance has been successfully completed, any required MOCs and MTFs have been completed, and the aircraft is deemed airworthy and returned

to operational service. A unit's Mission Capable (MC) rate is the sum total of FMC and PMC hours during the reporting period.

A related metric for analysis is a unit's Non-Mission Capable for Maintenance (NMCM) rate. NMC time is accrued when the material condition of the aircraft prevents it from being operated at an acceptable level of safety and is subsequently grounded. NMC time is further broken down into two sub-categories: Non-Mission Capable Maintenance (NMCM) and Non-Mission Capable Supply (NMCS). NMCS is the time that an aircraft is not available to fly mission due to the lack of a part to complete required maintenance actions. NMCM is the time, in hours, that an aircraft is not airworthy due to required maintenance actions (scheduled) or faults discovered during flight or inspection (unscheduled). The aircraft continues to accumulate NMCM time until the completion of an MOC or MTF for the maintenance action or procedure performed.

With HUMS equipped units, the hypothesis is that NMCM time should be appreciably reduced due to the system's ability to monitor and rapidly diagnose impending failures. The system should provide enough information during daily data transfer to sequence any required maintenance actions in during the next scheduled maintenance event. This increased efficiency from aircraft health monitoring and failure predictability, NMCM rates should decrease with the implementation of CBM systems on the airframe. An aspect to be noted is that only a fraction of the aircraft components have a plan to be actively monitored, limiting the overall potential of NMCM as a metric.

The final metric cited in this study is the amount of money expended by a unit on aviation repair parts, or class nine (CL IX) budget. These figures are derived from the

Department of Defense Operating and Support Management System (OSMIS) database. OSMIS monitors unit expenditures in repair parts, fuel, and petroleum, oil and lubricants (POL) reflecting the total sum of dollars spent by a unit on its assigned airframes. HUMS should theoretically reduce the amount of dollars spent on aviation repair parts with the extension of TBOs, enhanced health monitoring of vibrations throughout the airframe, and better efficiency of maintenance actions performed. It should be noted that this cost could still show an increase for HUMS over non-HUMS equipped units. This might be due to the increase in operational readiness and more significantly, flight hours for units utilizing CBM systems. As a unit is able to maintain increased levels of readiness it will be possible to take on additional missions and complete more flight hours with the same number of aircraft. This would come at an additional cost in fuel and probably repair parts as well, since the airframe would still undergo wear and tear with the increase in flight hours. This metric would be more effective if used with others to determine the overall cost spent per flight hour performed.

Unusable Metrics

Two of the principle objectives of CBM are to decrease the maintenance burden on the soldier and increase platform availability and readiness. This maintenance burden can be directly tied to the number of maintenance man hours (MMHs) performed by aviation mechanics, and maintenance test flight (MTF) hours performed by maintenance test pilots. While it is thought that CBM would improve general maintenance practices and subsequently reduce overall MMHs and MTFs required while increasing readiness and enhancing safety, significant limitations prevent these two elements from being used as viable metrics in the evaluation of CBM.

Maintenance Test Flights (MTFs) are classified as General Test Flights and Limited Test Flights. The General Test Flight is a detailed flight to test the airworthiness of the entire airframe in order to prove all systems and components are working as prescribed in the applicable aircraft maintenance manuals. General Test Flights are required after the completion of a Periodic or Phase Maintenance inspection, when an aircraft is removed from intermediate storage, after major aircraft overhaul or disassembly/reassembly of the aircraft, when accepting new aircraft into the inventory, during acceptance of an aircraft after a period of bailment, loan or lease, and whenever the unit commander or maintenance officer determines a general test flight is necessary to determine the airworthiness of an aircraft. Limited Test Flights evaluate the operation and performance of a specific system or component. In contrast to a General Test Flight, the limited only performs maintenance test flight procedures that directly evaluate the system(s) that were adjusted during the maintenance action. These hours are required in order to return the aircraft to a Fully Mission Capable (FMC) status³.

From the inception of the CBM program, it was believed that HUMS-equipped aircraft would substantially improve maintenance practices and the overall need for MTFs would be significantly reduced. With the constant monitoring of vibration analysis for component failure, along with the data collected to aid maintenance officers with rotor track and balance (RTB) or rotor smoothing, the advantages of HUMS with respect to MTFs seems obvious. While this aspect of aviation maintenance seems intuitive, finding data that reflects this change and further supports the claim that CBM will significantly reduce MTFs has proved to be challenging.

During the 2009 American Helicopter Society's Condition Based Maintenance Conference, Mr. Joshua Kennedy from AMCOM G3 presented a paper focused on the MTF benefits of HUMS. His methodology was to compile flight record data through a tail number analysis of aircraft, to include Apache, Blackhawk and Chinook airframes, MTF hours performed before and after HUMS installation. While the Apache data seemed promising, there was not enough unadulterated data clearly conclude that HUMS equipped aircraft would significantly reduce MTFs. To clarify, a majority of the flight data records (DA Form 2408-12) were excluded due to discrepancies in flight mission code and hours logged, etc, all of which are attributed to human error. In many cases, an aircraft is run up and test flown in conjunction with a mission, completing the maintenance test flight portion but failing to log a separate flight for the operational mission, artificially inflating the number of MTF hours completed. When comparing the Apache flight data over a three year period, the study had to eliminate 5,449 hours of flight time for incorrect mission symbols and 85,518 hours due to erroneous flight hour recordings.⁴ The end result from this already small period of observation, is a meager sample of flight data from which neither strong theory nor conclusive evidence can be drawn.

The majority of these discrepancies will be eliminated in the future with the implementation of CBM technology in the various airframes, but unfortunately the available data is not large enough now to allow us to draw strong conclusions for a reduction in MTF hours. In the future, this metric may prove to be valuable in measuring the effectiveness of CBM with overall reductions in troubleshooting, RTB and other

maintenance practices and should be addressed in the future when there is more flight data to examine.

Another unuseable metric is the Maintenance Man Hour (MMH) consisting of direct “hands-on” man hours spent performing a maintenance task or procedure. This period does not include the time consumed collecting tools or parts required to complete the task, but does include the time expended filling out forms and records.⁵ Reducing or eliminating lost man hours will, in turn, increase available manpower to execute the unit’s maintenance mission.⁶

Despite the difficulty in *measuring* a reduction in MMHs across the UH-60 fleet following HUMS installation, we are quite sure that the time required for certain maintenance procedures will significantly decrease due to HUMS. Examples include the oil cooler axial fan bearing, utilized to cool transmission oil with normal operating revolutions in the range of 23,000 RPMs, was normally inspected every 120 flight hours and replaced after 2500 hours.⁷ With a CBM equipped aircraft, the 120 hour inspection requirement is eliminated and the 2500 hour TBO is extended to 3240 hours.⁸ This change in maintenance procedures saves .75 MMHs per inspection and saves 0.6 hours of downtime per aircraft.⁹ In a normal OIF deployment, this would equate to 562 MMHs and 450 hours of downtime saved on an assault battalion (30 UH-60L helicopters) over a 12 month deployment. Likewise, the engine output drive shaft 120 hour inspections would be eliminated with CBM monitoring and would reduce 3.3 MMHs per inspection and another 1.8 hours in downtime. Again, translating these statistics to an OIF deployment would yield a net gain of 2,475 MMHs and 1,350 hours of downtime over a 12 month deployment.

Even more changes to maintenance procedures are being implemented which affect the MMHs expended performing aircraft run-ups or MOCs. Blackhawk tail rotor de-ice brackets and boot assemblies frequently break or wear down. The tail rotor de-ice bracket is often unused, especially on and OIF deployment, merely connecting and holding a cable to each tail rotor paddle in order to provide de-ice capability. The tail rotor boot assembly is a rubber boot or gasket which covers the gap between the tail rotor paddle and the retention plates, preventing sand, dust and other materials from working into either component and causing erosion damage. The bracket and boot components are often broken or damaged during routine maintenance inspections and actions. Replacement of this bracket or boot assembly normally requires balance verification with the installation of an aviation vibration analysis (AVA) kit and a dedicated aircraft run-up. On HUMS equipped airframes, aircrews will verify tail rotor balance on run-up during normal mission operations. The result with HUMS: a savings of 2.5 MMHs and 2 hours of downtime per replacement.¹⁰

One promising metric that was considered during this study was mission abort rate. A mission abort occurs when an operational aircraft assigned to perform a mission, becomes unable to perform its assigned task (PMC or NMC). This most frequently occurs during preflight or when the aircraft is run-up and a system fault is detected. Sometimes this occurs in-flight and may cause the mission to terminate or the aircraft to conduct a precautionary landing. In some cases, the commander or maintenance personnel deem that the airframe can still perform its mission, despite reaching a PMC status. These actions by the unit often disguise the numbers, accepting risk for the sake of mission accomplishment. The hypothesis is that CBM would provide maintenance

personnel and commanders with increased situational awareness with respect to impending failure as well as a more accurate health status of the airframe for risk mitigation should a failure occur during mission execution.

A study from AMRDEC in January 2009 referenced the mean time between maintenance abort for a handful of deployed and non-deployed units spanning a few years.¹¹ The information used in the study was provided by units fielded with the Unit Level Logistics System--Aviation (Enhanced) or ULLS-A(E), specifically from the electronic logbook forms (Form 2408-13) which compiled the maintenance event records with the corresponding malfunction event codes to determine how and why the mission was aborted. Many units have not been fielded with ULLS-A(E) thereby limiting the data sample size for both MA and MMHs. As cited in the MTF study,¹² the data entered into ULLS-A(E) is subject to individual aircrew error in inputting the correct writeup and codes, injecting uncertainty into the final results. Without this raw data from the aviation unit and the lack of widespread reporting, there is no consistent or reliable evidence to support the use of mission abort as a metric in this thesis. However, if mission abort rate and system failure codes were integrated into unit status reporting, MA could be an excellent metric for assessing the effectiveness of HUMS and a unit maintenance program, as well as identifying modes of failure and trend analysis in critical components.

Another metric examined in the formulation of this thesis was the aviation accident rates between HUMS equipped and standard aviation units. The theory behind this measure of effectiveness is that if HUMS increases aircraft health awareness of

maintenance personnel as well as failure detection, aviation accidents in CBM units would be lower in comparison to their non-equipped counterparts.

The cost of aviation accidents in the Army is staggering. The Army breaks its aviation related accidents down into classification codes, A, B, C being the most severe. A class A accident is defined as an event that results in a damage cost of \$1,000,000 or more and/or destruction of an Army aircraft, missile or spacecraft and/or fatality or permanent total disability. Class B is an occurrence where damage costs of \$200,000 or more, but less than \$1,000,000 and/or permanent partial disability and/or three or more people are hospitalized as inpatients. And finally, a Class C is when damage costs of \$20,000 or more, but less than \$200,000 and/or non-fatal injury resulting in loss of time from work beyond day/shift when injury occurred and/or non-fatal illness/disability causes loss of time from work.¹³ Over the past 12 years, aviation accidents have cost the Army more than \$16.2 billion and averaged \$539,281 a mishap and claimed 2,856 soldiers lives.¹⁴

The downfall of this metric is that, in itself, an aviation accident is not necessarily representative of a material or maintenance failure. In fact, a majority of aviation accidents are due to a myriad of causes like combat losses, crew coordination and communications errors just to name a few. These factors would have no direct bearing on the number of maintenance related aviation accidents. Furthermore, if we examined just those accidents related to maintenance we would have to exclude any event that was due to faulty maintenance practices, as this would have no bearing as a metric on the successfulness of CBM but rather on a training or procedural deficiency on the part of the maintenance program.

According to the data provided by the Army Combat Readiness and Safety Center, 4-101 Aviation and 5-101 Aviation each accumulated one Class A and two class C accidents between 2000 and 2008.¹⁵ No further information was provided as to the cause, findings or determination of the crash investigation boards so no worthwhile conclusions can be drawn from accident reports regarding the effectiveness of CBM. In the future Army Aviation may want to examine this metric to conclude if there is a correlation in maintenance related accidents between HUMS and non-HUMS equipped units.

Chapter Conclusion

This chapter has defined and evaluated the metrics that will be used in the analysis portion of this study. These metrics will be applied in detail in order to determine the overall effectiveness of CBM in aviation. The most metrics for meaningful comparison are Flight hours (FH), Operational Readiness (OR) rates, Non-mission Capable for Maintenance (NMCM), and CL IX (Air) aviation maintenance repair parts in dollars. As previously mentioned, other factors such as Maintenance Test Flights (MTFs), Maintenance Man Hours (MMHs) and Aviation Safety (Class A, B, C accidents), while showing great promise for future studies, will not be evaluated to determine the usefulness of CBM in maintenance operations.

¹Department of the Army, "DA Form 1352 Roll-up Reports for 4-101 and 5-101 Aviation from 2000-2008," Logistics Support Activity (LOGSA), Redstone Arsenal, 2009.

²COL (P) Warren Phipps, "Aviation Branch Day Briefing," Presentation to ILE Aviation Students, Command and General Staff College, Fort Leavenworth, Kansas, August 2008.

³Department of the Army, Department of the Army Pamphlet 738-751, *Functional Users Manual for the Army Maintenance Management System – Aviation (TAMMS-A)* (Washington, DC: Government Printing Office, 1999), 29.

⁴Joshua Kennedy, “Comparison of HUMS Benefits: Maintenance Test Flight hours,” presentation at the American Helicopter Society Condition Based Maintenance Conference, February 2009.

⁵DA Pam 738-751, 68.

⁶Department of the Army, Field Manual (FM) 3-04.500, *Army Aviation Maintenance* (Washington, DC: Government Printing Office, 2006), 1-4.

⁷Department of the Army, Technical Manual (TM) 1-1520-23-9, *Aviation Unit and Intermediate Maintenance Manual for UH-60A/L Helicopters* (Washington, DC: Government Printing Office, 2003), B-35.

⁸Army Research Development and Engineering Command (AMRDEC), Airworthiness Release (AWR) for UH-60A/L Helicopters with Integrated Vehicle Health Management System (IVHMS) Health Management System (HUMS) Installed (AWR 1346), 09 June 06, 4.

⁹MG James H. Pillsbury, “Condition Based Maintenance in Army Aviation,” *Army Magazine* (January 2006): 30.

¹⁰Army Research Development and Engineering Command (AMRDEC), Presentation to Ms Adams, U.S. Army G-3, Alexandria, VA, January 2009.

¹¹*Ibid.*

¹²Kennedy, 3.

¹³U.S. Army Combat Readiness and Safety Center, Homepage, http://asmis.army.mil/stats/pkg_definitions.class (accessed 23 April 2009).

¹⁴Military.com, *Army Aviation Accidents Top \$16 Billion*, <http://www.defensetech.org/archives/004530.html> (accessed 23 April 2009).

¹⁵US Army Safety Center, Data for 4-101 and 5-101 Aviation Class A, B, C, D accidents from FY 2000-2008.

CHAPTER 4

ANALYSIS

Purpose

The purpose of this chapter is to provide the analysis required to determine if CBM is advantageous in comparison to the current phase and periodic maintenance system. The first part of the analysis examines how the metrics defined in the previous chapter answer the aforementioned thesis questions. The subsequent synopsis will then reflect on the overall evaluation of the usefulness as well as the advantages and disadvantages of CBM in Army Aviation.

Method

In order to accurately assess the usefulness and efficiency of CBM, this study will observe the overall performance two assault battalions from the 101st Airborne Division. When the 101st Division returned from Iraq in March of 2004, under the brigade modularity concept, an assault aviation battalion was reassigned to 3rd Infantry Division for their upcoming deployment to Iraq. This aviation battalion had the original HUMS field test aircraft from Operation Iraqi Freedom and were transferred to 4th Battalion, 101st Aviation during reset actions from April to July 2004. Research in this study will compare overall of 4th Battalion, 101st Aviation (4-101 AVN) against a sister assault battalion in the same division, 5th Battalion, 101st Aviation (5-101 AVN). While some differences will exist between the two, unit Standard Operating Procedures (SOPs) as well as Tactics, Techniques and Procedures (TTPs) from deployment to Iraq will be almost identical.

Further analysis and research will refer to unit performance starting from July 2004 but will focus in on the timeframes when both units were deployed to Iraq (OIF III/IV from October 2005 to September 2006). The deployment periods are ideal because they are the periods when the units are mission focused and are provided the priority of support and missions to better evaluate the effectiveness of CBM. The intent of this analysis is to determine if CBM reaps a measureable financial reward when compared to phase or time-driven maintenance. The analysis of these aspects will provide the basis of the conclusions and recommendations found in the final chapter of this paper.

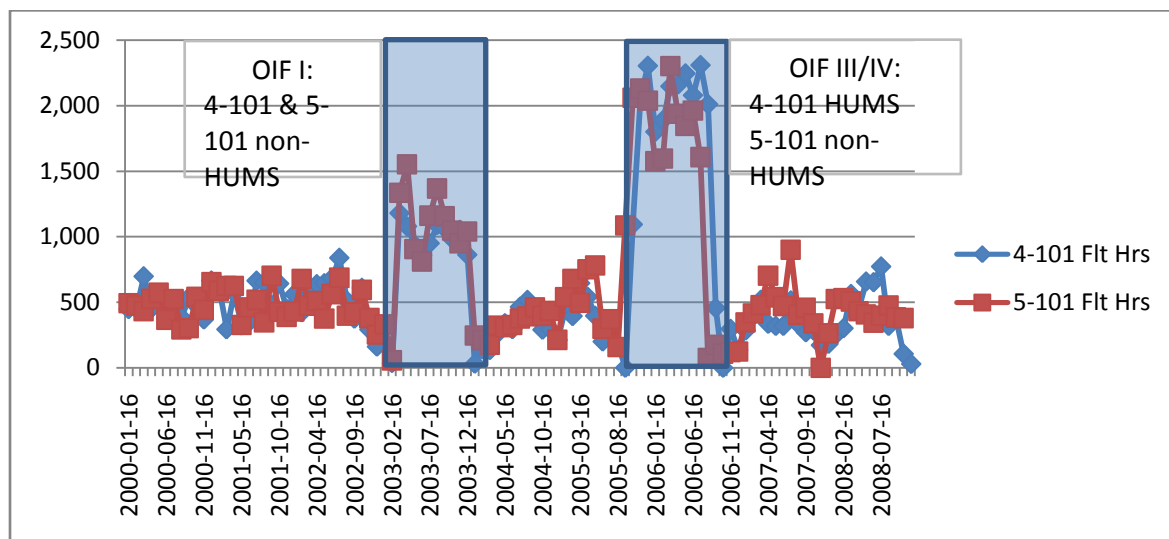


Figure 2. Total Flight Data comparison (2000-2008).

Source: Logistics Support Activity (LOGSA), DA Form 1352, 4/5-101 Aviation, 2000-2008.

Research Questions Answered

At this point it is possible to revisit the research questions that were formulated to guide the thesis. This chapter answers the primary question of, “Does CBM provide a

distinct advantage over phase or time driven inspections and component replacement in Army Aviation?” This chapter and preceding ones have served to answer each of the secondary questions.

Analysis of the data points toward a solid “yes”, but in order to address this question completely, the subordinate questions must be answered first. Fundamental to our understanding is the basic notion that CBM is not a turn-key, automatic or robotic system, where everything works perfectly and aircraft are repaired on a set predictable schedule. It is a system or program that enhances the way maintainers approach maintenance through increased visibility and predictability of the state and condition of unit airframes and their most vital components. While CBM will never get rid of phase maintenance, retirement and TBOs, it does give maintenance officers the metrics to track the health and usage of numerous critical components, extending and maximizing the lifetime use on the airframe.

Subordinate Questions

Subordinate Question 1: How Do We Measure the Overall Benefits and Costs of CBM?

As discussed in the previous chapter, the overall benefits can be illustrated with the use of FHs, OR rate, and NMCM, and CL IX (air) funds spent as metrics. As stated earlier, we will exclude MMHs, MTFs and aviation accidents from further evaluation in this study due to a lack of sample data or reliability for analyzing the data being examined.

When examining the flight hours completed during the 101st Airborne Division’s deployment to Operation Iraqi Freedom, the deployment timeline is apparent in the

fluctuations in flight hours performed. Using figure 1 as a reference, the unit's deployed at the end of September 2005 and the beginning of October 2006. The first reporting period during the deployment started in October and for the first two months, the performance was almost identical between the two battalions, with 4-101 completing only 15 hours more than their sister unit. In the remainder of the deployment, 5-101 was only able to top the HUMS equipped unit two times, in the months of January and April, for a total of 381 flight hours. Across the deployment, 4-101 decisively outperformed their sister battalion with an overall increase of 2070 flight hours. This significant accomplishment equated to a 10.2 percent flight hour improvement for the CBM equipped unit over the course of the deployment.

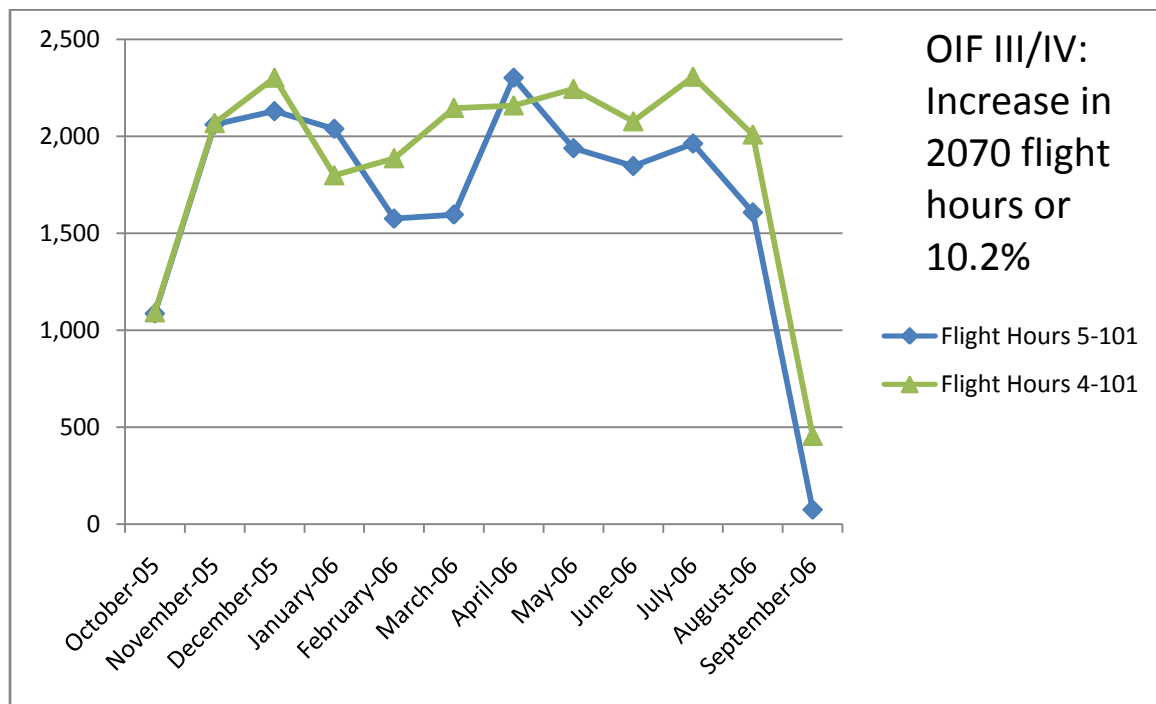


Figure 3. Flight hour comparison OIF III/IV

Source: DA Form 1352, Reports for 4-101st and 5-101st Aviation from 2000-2008

Over the same period, OR rates for 4-101st were again better than those of 5-101st Aviation. Referencing Figure 2, 5-101 was again only able to best the CBM equipped unit two times, in February and September, for a combined readiness difference of 1.1%. The remainder of the deployment showed a vast difference between the two unit's readiness levels. The HUMs equipped 4-101 Aviation demonstrated an overall increase of 2495 mission capable hours or 13.9% over the deployment. This readiness improvement was probably the reason why 4-101 was able to complete more flight hours during the deployment. This direct correlation between an increase in operational readiness and flight hours cannot be captured or easily translated into a monetary value, but can very easily be seen as strong indicators of the effectiveness of CBM at the unit level.

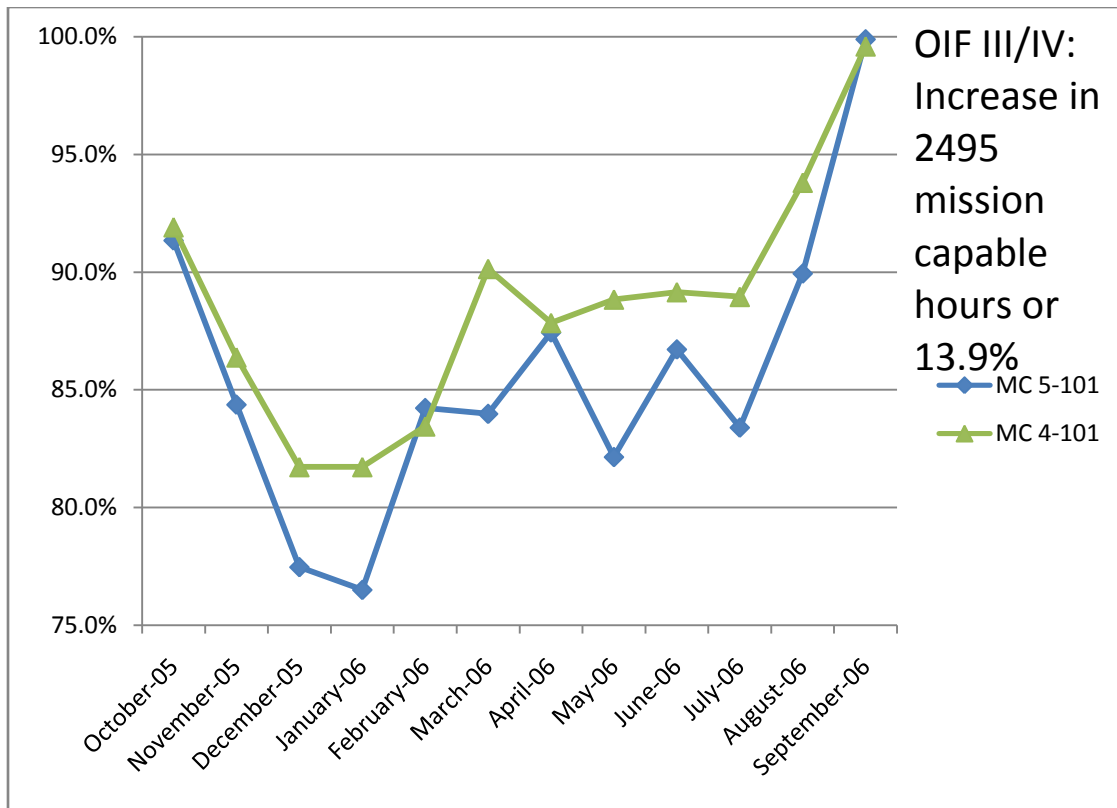


Figure 4. Operational Readiness comparison OIF III/IV

Following the same evaluation method, the NMCM metric showed similar improvement. Utilizing Figure 3 as a reference for NMCM performance, the HUMS equipped unit clearly illustrates an overall improvement in reducing maintenance downtime on the airframes throughout the deployment. While the difference in quantity is not as significant with this metric, 4-101 Aviation still showed an overall decrease in 172 non mission capable hours for maintenance or an equivalent drop of 6.9% NMCM time. While there is no way to further attribute this success to one or more elements of HUMS, it can be assumed that the addition of this system allowed maintainers to better utilize personnel and synchronize maintenance inspections and procedures due to CBM monitoring.

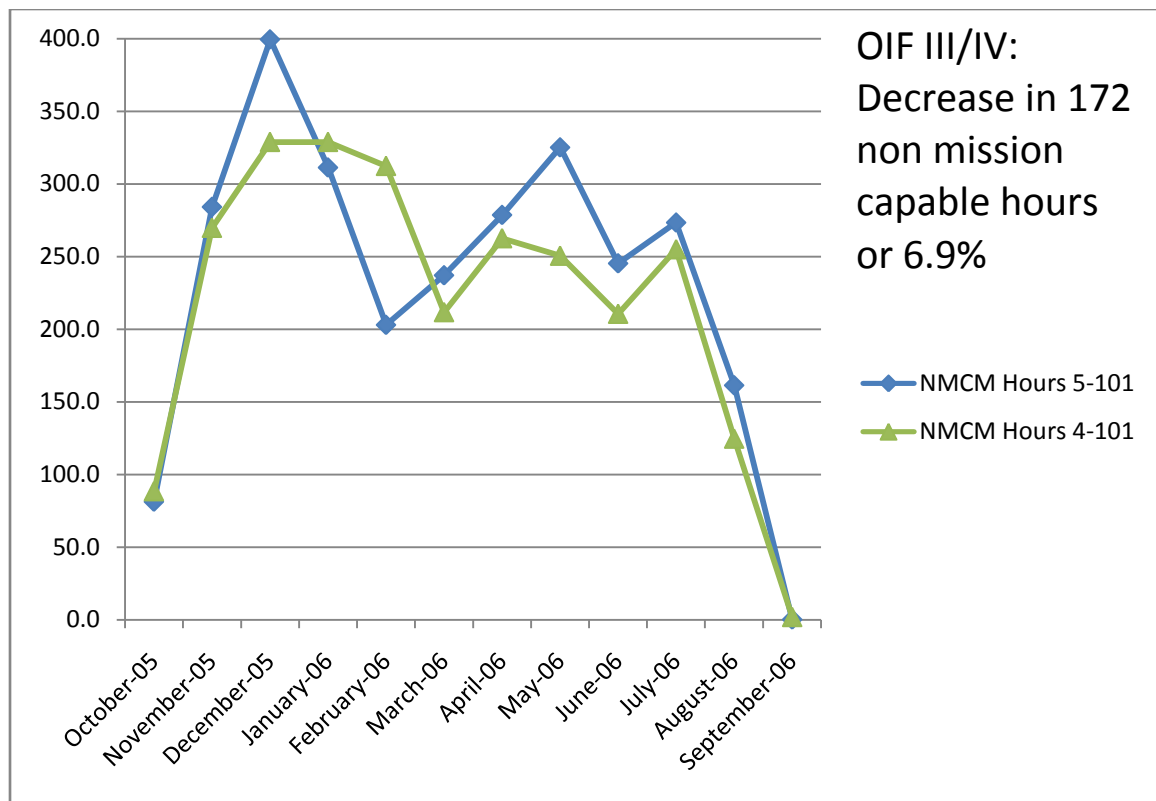


Figure 5. Non Mission Capable for Maintenance Comparison

The final metric of dollars spent on repair parts and fuel is a complicated one to address. While the amount of money spent on Class IX repair parts is a useful metric, by itself it does not show improvement in unit performance between HUMS and non-HUMS equipped units. In fact, overall expenditures in fuel and repair parts are higher for 4-101 when compared to 5-101 Aviation. While an increase in flight hours would logically lead us to an increase in fuel costs, explaining the trend in repair parts is a little more complicated. To truly understand this metric we must understand the relationships between flight hours performed and the repair parts consumed.

As previously mentioned, there is a correlation between flight hours and operational readiness. As the unit achieves higher operational readiness rates through

improved or more efficient maintenance practices, it is also able to perform additional missions. Regardless of whether this is a HUMS unit or not, this increase in flight hours performed will also drive an increase, at a relatively constant rate, in Class IX repair parts. This growth is due to the normal wear and tear components on an airframe, such as bushings and elastomeric bearings.

Where the differences appear between HUMS and traditional units are in the large components, especially those monitored for TBOs. The most significant of these differences now being that HUMS units are able to extend TBOs on several monitored airframe components. Now 4-101 is able to extend the oil cooler bearing TBOs an additional 1240 hours past those of 5-101 Aviation, thereby increasing the lifetime use of the component and decreasing Class IX dollars. This savings in dollars when compared to the number of flight hours completed serves as a better metric and will be highlighted in chapter 5.

Subordinate Question 2: Can CBM data accurately predict impending component failure and how closely does actual component failure come to established TBOs?

Based on vibration frequency data collected from HUMS equipped aircraft, HUMS engineers have developed vibration thresholds in order to observe the overall health of monitored components. With initial data tracking we can develop condition indicators (CIs) which monitor the operating parameters of the component in order to predict and detect impending failures. Further analysis helps to link these and new CIs to determine their modes of failure for the component through subsequent inspection at the unit maintenance level or depot teardown and rebuild facilities. The next step in this process is to track and define the failure modes for monitored components. Through

failure mode identification, maintenance personnel can modify current inspection methods to better anticipate component deterioration. The endstate of developing CIs is to more accurately predict component failure. The biggest benefit here is the ability to turn what would have been an unscheduled maintenance event (sometimes a catastrophic event) into a scheduled maintenance event. This conserves and enables resource management at the unit level.

The question of component failure in comparison to component TBOs, there is a substantial gap between the two. As previously stated, TBOs are established based on the mean time between failure for a component, adjusted further with a safety factor of three¹. As indicated earlier, this requirement for safety based on the mean time between failures reduces the lifetime use of the component in order to avoid the possibility of catastrophic failure. With the implementation of HUMS, aviation maintainers are able to track the health of the individual component, taking into account unique discrepancies from fabrication and material flaws. CBM has enabled units to extend previously established TBOs while enhancing safety.

A current example of the usefulness of extending TBOs can be found UH-60 oil cooler bearings reach TBO at 2,500 flight hours². Initial testing and data has extended their lifetime by an additional 1,240 hours³. During my deployment with 3rd Infantry Division during OIF III (January 2005 – January 2006), that would equate to an additional 5 to 10 months before that component would require replacement (based on aircraft flying between 100-200 hrs a month).

The utilization of CBM to enhance safety has been a highlight in previous studies and presentations. The most notable was from an Apache unit equipped with digital

source collectors (HUMS). On 5 April 2007, the unit suffered the loss of an aircraft and conducted an analysis of the CBM data from monitored components on the airframe. Subsequent analysis found that the static mast bearings on the tail rotor exhibited an above average frequency level accompanied by a “warm” temperature reading. While CBM data readings were not into a critical range, maintenance personnel immediately conducted an investigation into the static mast bearings of their entire fleet. The end result was another airframe exhibiting even higher frequency and temperature readings than the lost aircraft. The aircraft was immediately grounded and the entire swashplate assembly replaced. Upon further inspection at the depot level, the bearing assembly was found to have significant corrosion surrounding the ball and race indicating impending failure. The swashplate had passed all previous visual and periodic inspections. The internal bearing housing had rotated 90 degrees and the depot estimated 5-10 hours to complete failure. This example of CBM detecting a fault saved a \$16 million dollar aircraft, two crews scheduled to fly that day with more than 3000 flight hours, 5 combat tours, all married with a total of 12 children.⁴

Subordinate Question 3: Can component failure be predicted with enough time to provide supply request time?

The key to answering this question lies in data collection and failure analysis. As HUMS equipped units continue to fly and acquire data on airframe monitored components, units are better able to monitor and predict the impending failure of the item. What both the aviation industry and Army aviation are attempting to do is define three vibration frequency ranges which will establish normal operating range, precautionary or transient range and impending failure range. Normal operating range

will encompass normal vibration frequencies for all flight regimes. Precautionary range will signal maintenance personnel to closely monitor significant increases in vibration measurement and order replacement part. This will allow maintenance to forecast and sequence this action in with another scheduled inspection or procedure to minimize downtime and maintenance man hours. Impending failure range will dictate aircraft grounding for safety reasons pending the inspection and/or replacement of the component in question.⁵

At this time, there seems to be sufficient data to indicate that CBM will predict impending failure of monitored airframe components, but unfortunately it is extremely difficult to say whether this notification will come with enough time to request and receive this part without negative impact on the aircraft readiness. There are numerous factors which come into play, making this question difficult to accurately answer. First, as the amount of data acquired in varying flight regimes and environmental conditions increases, the established normal, precautionary and impending failure ranges will be adjusted to improve our ability to predict material failure. More importantly, the supply system priority and the deployment status of the unit would yield substantial differences in supply requisition time. In general, HUMS appears to provide deployed units with the necessary time to identify major components with enough lead time to procure a replacement part without accruing unnecessary downtime.

It should also be noted that this research question, although final to commanders' concerns for optimal readiness of airframes, is ancillary to this study. The question of whether the CL IX (air) supply system is responsive to the needs of deployed units is a

subject for separate research. The inability of the supply system to provide on-time component replacement is evidence neither for or against the value of CBM.

Subordinate Question 4: Does CBM reduce maintenance man hour and test flight requirements? By how much?

During investigation into this study, MMHs and MTFs were identified as unuseable metrics due to the difficulty tracking and substantiating these metrics with raw data. As previously stated in the metrics chapter, MMHs are seldom tracked during deployment and MTFs lack a sufficient quantity of unadulterated flight data, making their use in this study inconclusive. “Nobody does a manpower analysis in combat,” says Christopher Smith, AMCOM G3, Director of CBM. “We tend to see units using the additional manpower to keep more aircraft flying.” A young NCO in the 101st probably sums it up best when he stated, “Sir, these aircraft with CBM free up enough time to allow us to better maintain the aircraft that don’t have CBM.”⁶ However, with the implementation of CBM programs into existing maintenance practices and procedures, a resultant reduction in MMHs cannot be ignored. Likewise, the advantages of CBM with respect to maintenance test flights, especially track and balance, seem to provide an especially useful tool in maintenance operations.

Another example to help answer this question is the extension of AH-64 APU clutch and mount inspection intervals from 250 to 500 hours, saving 28 man-hours per inspection and cutting downtime by 9 hours an aircraft⁷. Using this approach with the 101st Aviation unit data, 5-101 will be required to visually inspect and remove this oil cooler bearing assembly every 40 and 2000 hours respectively, while 4-101 will utilize the vibration monitoring provided by HUMS to determine the health based usage of the

component. This will save them a minimum of 0.4 and 6.3 MMHs per inspection and replacement⁸, or approximately 201 MMHs for inspections and an additional 63 MMHs in replacements over the course of the deployment.

Rough estimates are that 5 to 15 percent of a unit's flight hours are expended for MTFs.⁹ During the conduct of test flights, the aircraft is not considered airworthy and is not available for missions until the MTF is signed off complete. The benefit of HUMS is not a cost savings or even cost avoidance but rather trading MTF hours for flight hours conducted directly to accomplish the operational mission. According to a recent air worthiness release for HUMS-equipped aircraft, the test flight requirements for these aircraft are significantly reduced due to vibration monitoring.¹⁰ After an aircraft has been test flown and released from scheduled maintenance or a component change, rotor smoothing adjustments can be made without necessitating an additional maintenance test flight. This MTF reduction will directly affect the trade of MTF hours for mission hours. An additional note to highlight is a recent study completed on the AH-64 which shows a decrease from 2.56 MTF hours per 100 flight hours to 1.12 MTF hours per 100 flight hours, for a total change of 56.25 percent.¹¹

Subordinate Question 5: Does CBM increase operational readiness rates and flight hours? By how much?

Initial data provided by AMCOM cited an increase in operational readiness between 4.4 and 5.2 percent for all three airframes (UH-60, CH-47 and AH-64).¹² They further reported an increase of 5 to 8 percent FMC rate in CBM equipped units when evaluated over identical units in OIF.¹³ These higher FMC rates often manifest themselves in an increased flight hour rate as discussed in previous paragraphs. "We

recently had a CBM equipped Combat Aviation Brigade (CAB) return that flew over 100,000 hours in 12 months on 105 aircraft. Nobody has ever done that before – we would like to think CBM had a little to do with that.”¹⁴ While these numbers give us a starting point, we have to dig deeper to raw data before conclusions can be drawn with respect to the effectiveness of CBM.

As stated in the first subordinate question in this thesis, CBM’s contributions to the 101st aviation unit scenario was substantial. Flight hours, the major metric for performance in an aviation unit was lop-sided in favor of the HUMS-equipped battalion. Over their deployment to Iraq, 4-101 Aviation, clearly out performed its sister unit by 2,070 flight hours, representing an astounding 10.2 percent increase in efficiency. The same pattern holds true for the units’ operational readiness rates. 4-101 Aviation overshadowed the non-HUMS equipped battalion by 2,495 mission capable hours, an overwhelming 13.9 percent increase, over the deployment to Iraq. With these numbers, its is clear that CBM provides a distinct advantage in flight hours and readiness when compared to traditional aviation units.

Subordinate Question 6: What is the overall cost advantage to using CBM?

Costing is hard to use as a metric of success. What is the additional cost benefit of an additional 1 percent of readiness and aircraft availability? We can look at this two different ways. One is to look at the cost per man hour saved or the cost savings from Class IX aviation part replacement, or even maintenance flight hour savings. Sure, you can use stats like the maintenance test flight savings are running between \$2.6 and 9.3 million for the Blackhawk and Apache respectively, but as previously stated, man hours are not tracked in combat and are loosely estimated while back in garrison. Instead the

additional readiness lends itself to additional flight hours per aircraft due to the reduction in scheduled maintenance. AMCOM equates the advantage of CBM to providing the unit with the capability of flying an additional 3000 hours over 12 months,¹⁵ which is like giving the unit an additional 3 aircraft for the duration of the deployment.

But rather than attempting to loosely convert performance parameters into monetary gains, a different approach to modeling is required. Similar to the efficiency models used by Federal Express (FedEx) or the airline industry, Army Aviation has to develop a way to effectively assess aviation unit performance. FedEx uses a model which tracks the efficiency of their business by the dollars spent per kilogram or cubic meter flown. Similarly the airlines track the number of dollars spent per seat mile flown. From these examples, aviation has adapted a similar design model for evaluating performance efficiency, which we shall now entertain.

Model to Evaluate Monetary Effectiveness in Aviation Units:

Dollars per Operational Readiness Hour = Cost / (operational readiness x flight hours)

The current design used to evaluate the effectiveness of CBM is dollars per readiness hour, or the aviation total cost spent divided by the operational readiness times the flight hours performed. To further understand this model, we will define each of its subcomponents: cost, operational readiness and flight hours. The cost metric we previously defined includes all costs required to accomplish flight missions. Costs included in this study are the sum of the unit's fuel, POL and aviation repair parts and are derived from the OSMIS database. Operational readiness and flight hours performed are metrics obtained from the monthly unit readiness reports (DA Form 1352).

Applying this model to the 101st Aviation scenario, highlights a continuing trend for CBM. From the illustration in Figure 4, both units exhibited an increasing trend in dollars spent per flight hour as the deployment progressed. This increase is probably due to the heavy reliance on unit PLL and benchstock in the beginning and a push toward restocking and replenishing prior to redeployment. Regardless, the HUMS equipped 4-101 Aviation's cost per operational flight hour ranged from 882 to 2296, averaging 1752, while their sister battalion, 5-101 Aviation, ranged 253 to 5529 per flight hour, averaging 2535 over the deployment. The difference between the battalions over the course of the deployment was \$783 per operational flight hour or a 30.9% cost advantage for the CBM unit.

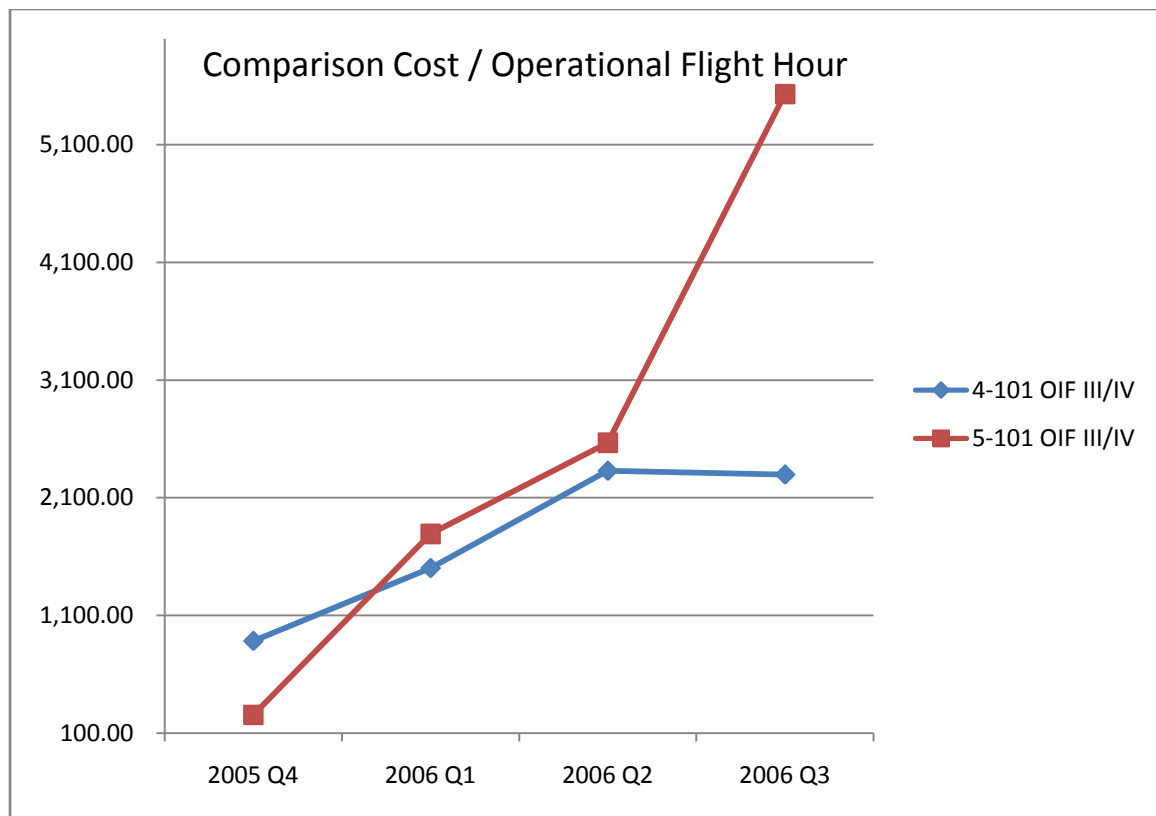


Figure 6. Cost per Operational Flight Hour comparison.

While this seems like a huge difference, a second look at the data points might shrink the significance of this metric. The major reason for this shift in weight is due to the short span of time covered in the analysis. While the flight hours and operational readiness data is provided monthly through monthly unit status reports, the fiscal numbers are reported by quarter, providing only four data points over the deployment. Because the number of monetary data points within the sample is extremely small, the significance of the result is questionable. Further analysis should be completed in order to provide convincing evidence to support the conclusion that CBM provides a cost advantage over traditional maintenance practices.

Chapter Conclusion

This chapter has applied critical and meaningful metrics from the previous chapter to analyze and assess the overall effectiveness of CBM. Through a comparison of like aviation battalions in the 101st Airborne Division, HUMS has demonstrated a superiority over traditional units in flight hours, operational readiness, and non-mission capable for maintenance time. While it has shown an advantage in financial savings using the employed model, the small fiscal expenditure warrants further research before concluding that CBM provides a cost advantage per operational flight out completed.

¹Christopher Smith, AMCOM, CBM Director, Email correspondence with author, 22 September 2008.

²Department of the Army, Technical Manual (TM) 1-1520-23-9, *Aviation Unit and Intermediate Maintenance Manual for UH-60A/L Helicopters* (Washington, DC: Government Printing Office, 2003), B-35.

³Army Research Development and Engineering Command (AMRDEC), Airworthiness Release (AWR) for UH-60A/L Helicopters with Integrated Vehicle Health Management System (IVHMS) Health Management System (HUMS) Installed (AWR 1346), 09 June 06, 4.

⁴MG Myles, "Keynote Address," presentation at the American Helicopter Society Condition Based Maintenance Conference, Huntsville, AL, February 2009.

⁵Christopher Smith, "Condition Based Maintenance," presentation at the Army Materiel Command, Condition Based Maintenance Summit, July 2008.

⁶Smith email correspondence.

⁷TM 1-1520-23-9, B-35.

⁸Ibid.

⁹Joshua Kennedy, "Comparison of HUMS Benefits: Maintenance Test Flight hours," presentation at the American Helicopter Society Condition Based Maintenance Conference, Huntsville, AL, February 2009.

¹⁰AMRDEC AWR, 4.

¹¹Kennedy, 4.

¹²Smith email correspondence.

¹³Ibid.

¹⁴Ibid.

¹⁵Ibid.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Research Conclusions

The study of the effectiveness of CBM in Aviation has generated several conclusions and recommendations. First, CBM has demonstrated a clear advantage over traditional maintenance methods through the utilization of vibration analysis. This advantage has been demonstrated by the application of several key metrics to similar Army aviation battalions in combat. This monitoring has proven to be superior over the method of time driven component changes and visual inspections. With the advent of the HUMS and similar system technologies, vibration analysis has become a decisive tool in enhancing the efficiency and effectiveness of aviation maintenance programs. The key to unlocking the true potential of this system will be through proactive maintenance integration and establishment of proper methods of evaluation.

Integrating CBM into current maintenance practices is an ongoing, dynamic process. Several aspects of both the maintenance and logistics specialties come into play and must be properly synchronized to empower success at the tactical level in aviation units. CBM should seek to alter maintenance practices through changes in unit reporting, maintenance test flight requirements, inspection frequency, and component failure detection. These perspectives will be addressed later in the recommendations portion of this chapter.

The final step in synchronizing CBM into the current maintenance operations is by developing methods to evaluate the effectiveness of the program. These metrics will assess both the status of the aviation unit's overall efficiency and the performance of the

maintenance program. Through flight hours, operational readiness, accident reporting and the dollar cost per operational flight hour, we can evaluate the success of an aviation unit's maintenance program. This maintenance program will feed off of these metrics in addition to mission abort rates, non mission capable for maintenance hours and material related accident reports. These revised metrics will be discussed in the following segment of this chapter.

Recommendations

This segment of the study will be divided into two subsections: Maintenance practices and Evaluation metrics. The maintenance practices section will cover the major challenges and changes with integrating CBM systems into future Army aviation operations while the evaluation metrics section will address methods of quantifying performance for aviation units in the future.

Army aviation as a whole, will have to re-examine how we conduct business in maintenance following the effective integration of HUMS into the fleet. Days from the completion of this study, I received information from AMCOM reinforcing many of the areas of focus within this recommendation.¹ The first of the proposals centered on the possible reduction in Maintenance Test Flight requirements, especially those involving main and tail rotor track and balance. With an integrated vibration monitoring system on board the aircraft, it seems a logical step to begin making slow to the test flight requirements. Keeping safety in mind, minor trim tab and weight adjustments to the flight controls for the purpose of rotor smoothing, can be performed without requiring a maintenance test flight.² The second proposal involved the elimination of the remaining 120 hour vibration inspections that were previously accomplished with the aid of the

AVA kit. These include the engine oil cooler and the engine output shaft vibration checks. With a HUMS equipped aircraft, these components will already be monitored throughout normal operational flights. Any adverse vibrations and trend data will be captured by maintenance personnel and planned accordingly into the scheduled maintenance plan. This program will effectively maximize supply and maintenance lead time, minimizing downtime and enhance airframe readiness.

Another recommendation to maintenance practices would reduce or possibly eliminate obsolete maintenance actions like Army Oil Analysis Program (AOAP) sampling. The purpose of the AOAP samples is to detect the breakdown of mechanical components in transmissions, gearboxes, etc. Current procedures call for AOAP samples to be taken every 40 flight hours. This sampling takes 0.5 MMHs to remove and replace the cowlings following an oil sample of the tail and intermediate gearboxes. These samples often have various impurities introduced by the crew chief due to the location and difficult method of sampling. As a result approximately 20% of all samples are deemed invalid and the maintenance procedure requires a complete drain, flush, run-up to normal operating temperatures and re-sampling for the affected gearbox, further increasing the cost in terms of MMHs, gearbox oil, and sampling costs.³

With HUMS equipped aircraft, the accelerometers collect vibration data to monitor the friction and subsequent breakdown of these components. AMCOM is currently recommending the 40 hour AOAP samples be amended to every 720 hours. This would significantly reduce the MMH burden on the crew chief, and the costs for gearbox oil and AOAP sampling. The very nature of HUMS vibration monitoring, and its performance in this study, permits us to recommend without hesitation the

elimination of AOAP sampling in HUMS-equipped airframes as redundant and unnecessarily wasteful of manpower, material, and logistical assets on the battlefield.

Another recommendation for change in the maintenance area has already seen substantial change in recent years. The extension of component TBOs has made great advances with the advent of HUMS. In a maintenance publication dated May 2003, oil cooler assemblies had an established TBO of 2000 hours, a far cry from the HUMS extended 3240 hours today. In dozens of other components we are seeing a paradigm shift from the old mean time between failure derived TBO to the new condition or health based component usage program. As long as this change keeps safety in mind, I foresee this change continuing for the majority of airframe critical components.

Continuing with this change in TBOs, our maintenance reporting procedures need to incorporate additional information to ensure we capture critical information about airframe components and unplanned events. These changes need to occur at both the unit and depot levels, in order to properly share information with AMCOM and other agencies. The first recommendation for change surrounds the monthly unit status report (DA Form 1352). This revised version of the 1352 should include any flight mission abort data to include codes which define the system failure, time or duration of the event. Mission abort data will help maintainers and logisticians alike by providing trend analysis, environmental concerns from sand to high heat conditions, as well as possible field remedies and work arounds for these challenges. This aspect of trend analysis and failure mode identification will be addressed later as a possible area for future study.

Another addition to the 1352 should be the reporting of major components that exceeded vibration thresholds and required replacement. This information should be

tracked and passed to depot personnel for further investigation. Upon receipt of such components, depot personnel will conduct a thorough analysis and investigation into the cause of the failure or event. The information derived from these investigations will again provide maintainers and logisticians with an insight into the modes of failure for a given component. At endstate, the data provided from units and depot rebuild facilities will help AMCOM integrate new and improved maintenance procedures and perhaps product development across Army aviation.

A Design Model for Monetary Evaluation of Condition Based Maintenance

As stated previously, the current evaluation design draws from the FedEx (dollars per kilogram or cubic meter flown) and Airline concepts (dollars per seat mile flown).

Dollars per Operational Readiness Hour = Cost / (operational readiness x flight hours)

In order to more effectively assess this model, we must make a two fundamental changes to the formula. First, correctly define what monetary aspects are to be included in the cost metric. This element was previously defined as all costs required to complete aviation missions, to include fuel, POL and repair parts. After close review of this metric, particularly in light of recent spike in fuel prices and the direct relationship between flight hours performed and fuel consumed, an inflation factor would have to be introduced and the fuel numbers should be eliminated in order to gain accuracy in a true comparison of the cost per flight hour.

The elimination of fuel costs in this model would take into account the dynamic nature of gas prices and their overall effect on the model. One reason being that fuel cost fluctuations will significantly influence the overall dollars spent and negatively impact

the model's ability to compare previous and future years to evaluate the effectiveness of Condition Based Maintenance, or aviation efficiency in general. Another reason to exclude fuel costs from this design is that fuel consumption is directly proportional to the number of hours flown. While this in itself is not a glaring reason to abandon the fuel metric, when coupled with the fluctuation costs it exponentially compounds the problem of trying to evaluate system effectiveness.

While this would not be useful in accurately forecasting a unit's fiscal budget based on a given number of flight hours, it removes major fluctuations in costs due to changes in fuel prices. In this study, both units were evaluated simultaneously, reducing the overall effect of inflation over the one year deployment. However, when attempting to evaluate units over different time periods, it would be necessary to introduce a factor to account for inflation.

While it is not necessary to prove the effectiveness of HUMS in this thesis, another aspect of the cost metric that should at least be addressed is the contractor maintenance cost. Contractor maintenance is normally provided at the brigade level but is often passed down to battalion's to assist the maintenance company workload. The contracts are serviced at the installation, region or theater level and are often covered under the Defense Supplemental Appropriations Bill approved by Congress. An accurate depiction of the true costs incurred from these contract maintenance personnel would be difficult to ascertain given their varying levels of experience, qualifications and supervisory roles. If the costing model seeks to gain a true dollar amount for the maintenance effort exerted in sustaining flight operations on a per hour basis, then consideration should be taken for the contractor costs.

The second change to the formula is to modify the denominator in order to increase the overall accuracy of the metric. Currently, all flight hours are included in the costing equation, when not all flight hours completed are linked to the accomplishment of the mission. To correctly reflect only the mission related flight time we must deduct the number of maintenance flight hours conducted from the total. This will provide us with the following cost per readiness mission hour equation.

$$\text{Dollars per Operational Readiness Mission Hour} = \text{Cost} / (\text{operational readiness} \times (\text{flight hours} - \text{maintenance test flight hours}))$$

When we can more accurately monitor cost data through the exclusion of fuel consumption and the inclusion of maintenance test flight hours and contract maintenance amounts, this metric will be more precise and will better illustrate the effectiveness of CBM in the future.

Continued Study

With new technologies and systems like HUMS being developed and adopted constantly, we need to improve our methods for integrating and assessing the changes in our new maintenance procedures. In order to do this we must correctly identify key systems to aid us in performing our mission and effective metrics for evaluating our performance. Future research into this subject should strive to further develop the dollar per operational readiness mission hour model and its associated metrics.

As more CBM systems are fielded across the fleet, aviation maintainers should continue to address the role of MTFs and mission abort events as possible metrics for performance evaluation and future preventative maintenance practices. While the MTF study conducted was unable to establish a sizeable data set to lend significance to the

findings, the preliminary data looks promising and warrants further investigation to determine its validity. Mission abort events are another important area to focus study. The information and results obtained from these events will lend to predicting impending failure, identifying failure modes and environmental conditions as well as developing remedies and solutions to prevent these problems from manifesting in the future.

¹Army Research Development and Engineering Command (AMRDEC), Airworthiness Release (AWR) for UH-60A/L Helicopters with Integrated Vehicle Health Management System (IVHMS) Health Management System (HUMS) Installed (AWR 1346), 09 June 06, 4.

²Ibid., 4.

³Jason Lawler, "Reliability Centered Maintenance, UH-60," presented at the American Helicopter Society Condition Based Maintenance Conference, Huntsville, AL, February 2009.

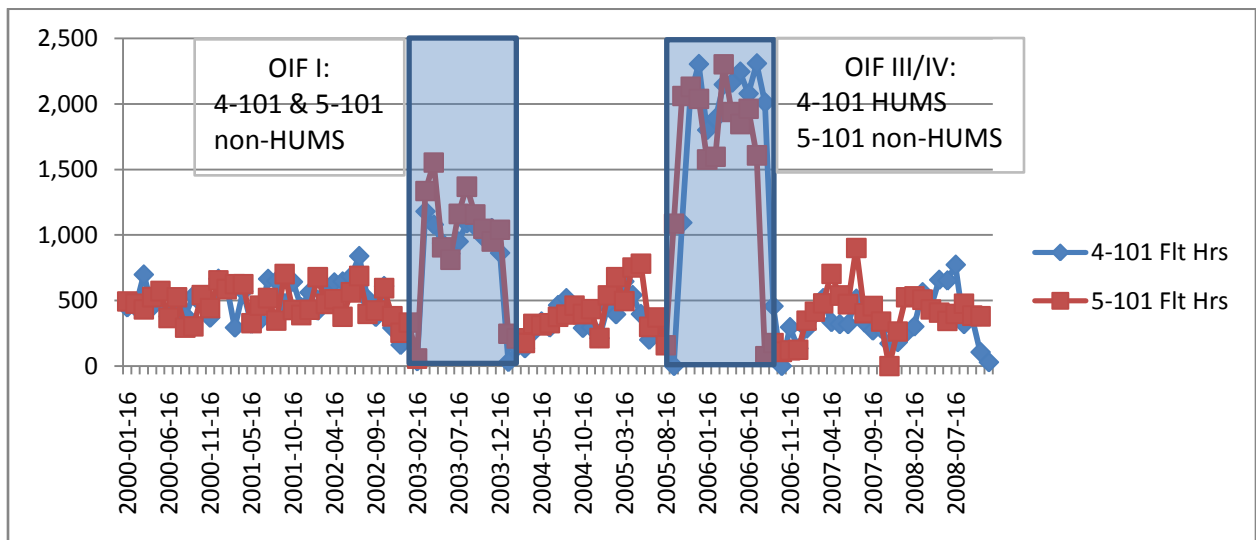
APPENDIX A

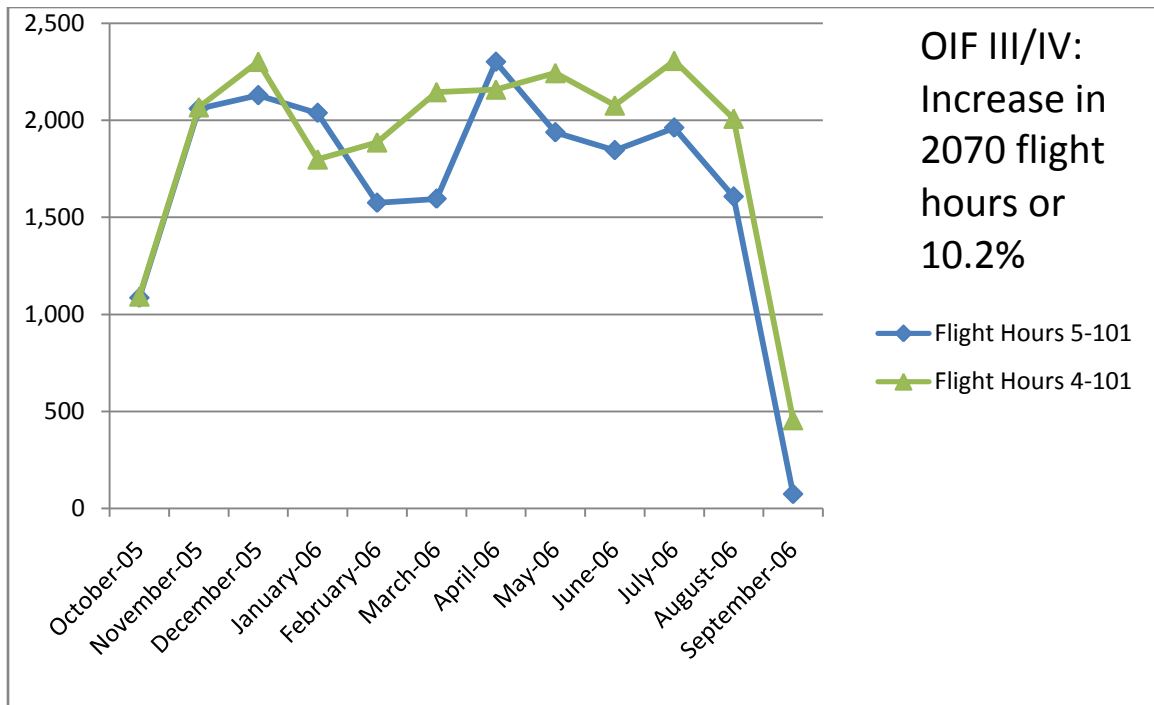
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AH64A	87-0483	AGA	744	187		A2/13	0	0	0	544	10	4/0	
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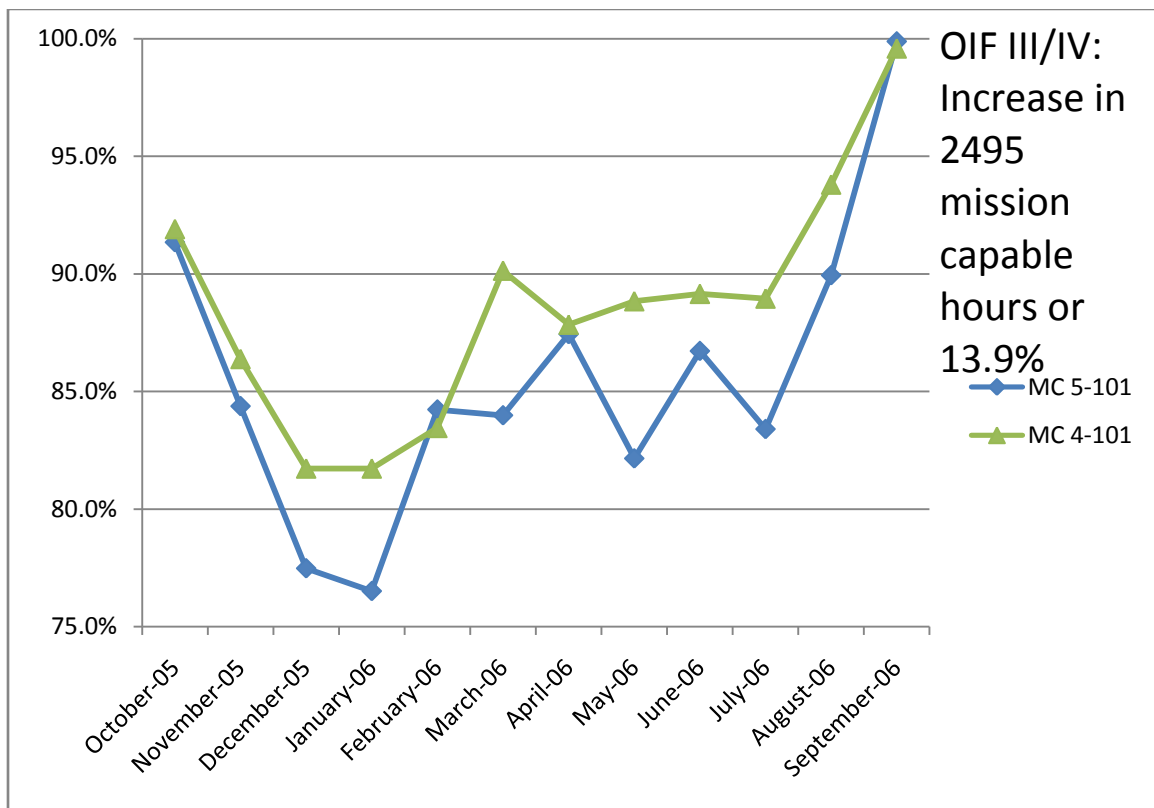
Figure 3-2. Sample of a completed DA Form 1352

Sample of a completed DA Form 1352 (DA Pam 738-751)

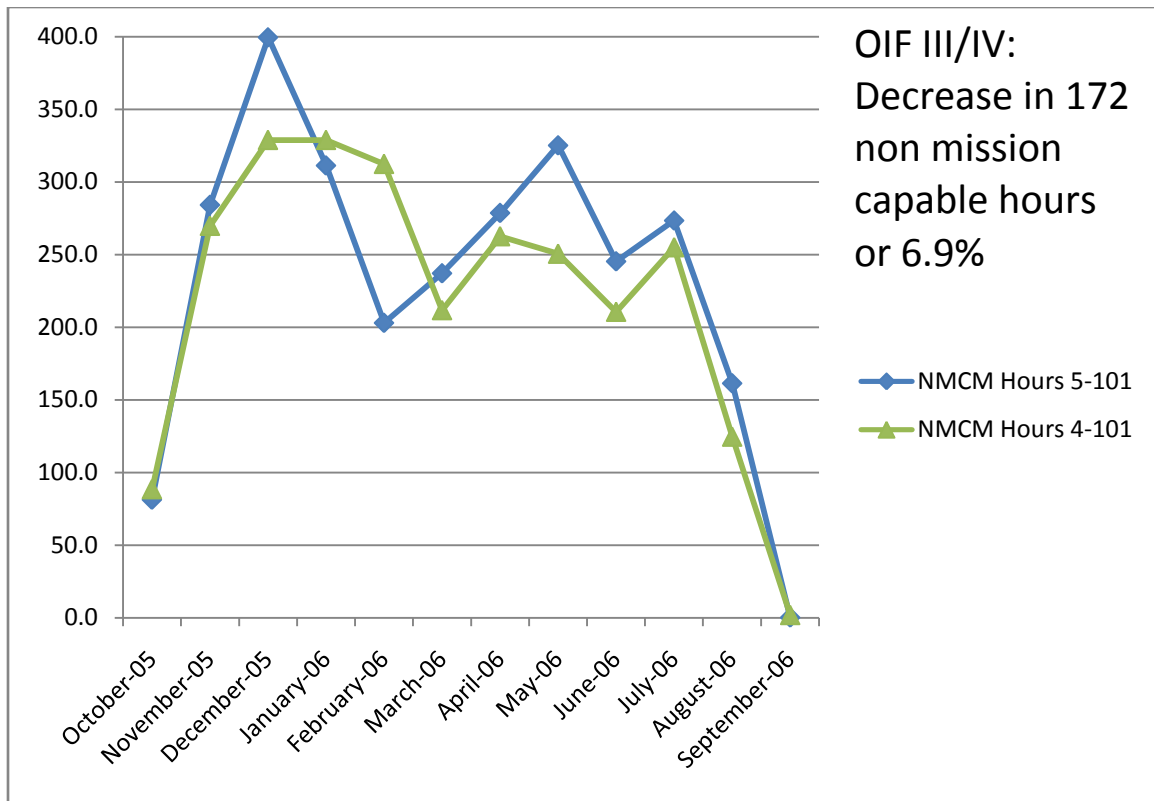




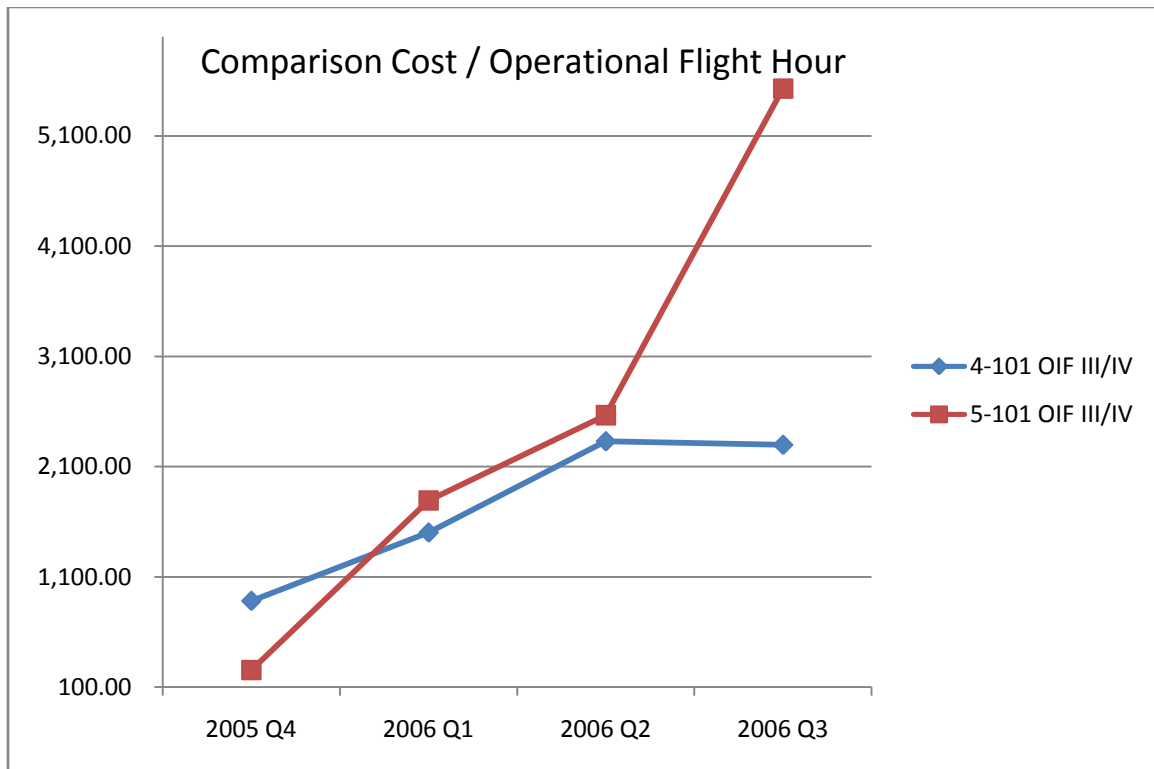
Flight Hour Comparison OIF III/IV



Operational Readiness Comparison OIF III/IV



Non-Mission Capable for Maintenance Comparison OIF III/IV



Cost per Operational Flight Hour Comparison OIF III/IV

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